LLNL-CONF-640181

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Qualification of the ITER CS Quench Detection System using Numerical Modeling

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July 2, 2013

MT-23
Boston, MA, United States
July 14, 2013 through July 19, 2013

Qualification of the ITER CS Quench Detection System using Numerical Modeling

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***Abstract*— The ITER Central Solenoid (CS) magnet needs to be protected against overheating of the conductor in the event of the occurrence of a normal zone. Due to a high stored energy and slow normal zone propagation, the normal zone needs to be detected and the switchyard needs to open the breakers within 2 seconds after initiation of the normal zone. The CS will be discharged on a dump resistor with a time constant of 7.5 seconds. During operation of the CS and its interaction with the PF coils and plasma current, the CS experiences large inductive voltages from multiple sources, including nonlinear signals from eddy currents in the vacuum vessel and plasma current variation, that makes the task of detecting the resistive signal even more difficult. This inductive voltage needs to be cancelled by the Quench Detection (QD) hardware (selection of favorable signals, bridges, filters, etc.) and appropriate processing of the QD signals in order to reliably detect the normal zone initiation and propagation.**

Two redundant schemes are proposed as the baseline for the CS QD System:

- a scheme with Regular Voltage Taps (RVT) from triads of Double Pancakes (DP) supplemented by Central Difference Averaging (CDA) and by digital suppression of the inductive voltage from all active coils (CS and PF). Voltage taps are taken from helium outlets at the CS outer diameter.

- a scheme with Cowound Voltage Taps (CVT) taken from cowound wires routed from the helium inlet at the CS inner diameter.

Summary of results of the numerical modeling of the performance of both baseline CS QD Systems are presented in this paper.

***Index Terms*—Quench Detection, Central Solenoid, ITER**

I. Introduction

The stored energy in the CS reaches 4 GJ. In the event of the initiation of a normal zone (NZ), the stored energy would be deposited in a very localized region and could destroy the Central Solenoid. Therefore it is essential to detect the NZ appearance and dump the energy quickly. The electrical method of voltage detection remains the quickest and most reliable primary quench detection method. Quench detection methods based on helium expelled from the coil or local increase of pressure are slow, and mass flow and pressure change are difficult to distinguish from non-quenching events with large heat release, like plasma initiation or disruption.

Quench detection in the CS by electrical method is nonetheless very challenging due to a large inductive signal coming from too many sources. Since the quench detection system only has to detect resistive voltage, the inductive signal is frequently called noise for QD purposes.

There are 5 electrically independent CS modules, 6 independent PF coils, plasma current and passive elements (vacuum vessel) to cope with. During plasma initiation the inductive voltage goes up to 11 kV. The level of resistive voltage at which the circuit breaker needs to open to evacuate the energy from the magnet is 300-500 mV. In order to have a reliable recognition of the NZ, the signal to noise ratio needs to be 10. Thus rejection ratio of the inductive noise must be an incredible 200,000 if someone would like to have a single QD circuit per CS module. This is no technology for that today. We have 20 Double Pancakes (DP) in a CS module and if we monitor DP signals, we reduce the voltage cancellation requirement by factor of 20, which makes it more manageable.

Several implementations of the ITER CS QD have been investigated so far. A scheme with the pickup coils (PCs) was proposed by Y. Takahashi et al [1]. It was shown [2-5] that the DP voltage signals give similar sensitivity as the pickup coils. Because of that, the pickup coils were removed from the viable options for quench detectors due to a high risk of mechanical failure or electrical breakdown. They cannot be repaired.

The next study on the QD was performed by a Commissariat a L'Energie Atomique (CEA) group [6,7]. They explored only initiation of the plasma event as a design driver. They assumed that the disruption can be blanked effectively for 3.5 s, since inductive noise will decay to a lower level after blanking and all the currents in the PF and CS system are decreasing in the initiation event.

The CEA QD scheme of choice is a VT-based system of two parallel-optimized central difference averaging (CDAs) with blanking. The CEA group showed that if the voltage threshold would be 0.55 V then with 3.5 s blanking it is possible to suppress the noise to the same level for initiation. This sensitivity implies that the signal to noise ratio would be about 1, which is unacceptably low. Also, if the quench occurs during other points of scenario, like plasma disruption, these parameters will not protect the CS.

Therefore, it was decided to develop two independent QD

Manuscript received July 15, 2013. This work performed under the auspices of the U.S. Department of Energy by Oak Ridge National Laboratory under contract DE-AC05-00OR22725 and by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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systems with more effective inductive noise suppression. One system would be based on co-wound voltage taps (CVT) and regular voltage taps (RVT) that would be a secondary QD system. The rationale of using two systems is that although CVT is much more sensitive and therefore reliable if it functions well, but it is not repairable. The RVT system is reparable, and if needed, it can be re-installed even outside of the ground insulation.

A. *Requirements*

The normal zone voltage at the peak current in the CS of 45 kA develops 0.3 V over the length of about 3-4 m at 20 K in the 13 T field. The quench detection needs to suppress the inductive noise to a level of 50-60 mV within 1.5 -2 s after the voltage exceeds the threshold value in order to make the threshold of 0.3-0.5 V reliable and prevent overheating of the conductor in the quench origination area above specified values.

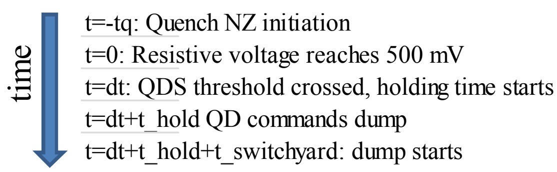

Fig. 1. Timeline of the quench evolution and QD actions

QD shall prevent dump if normal zone voltage is less than 0.3-0.5 V.

B. *Quench origination and evolution; QD system response*

The general timeline of the events monitored by the QD system is as shown in Fig.1. Let's suppose that as a result of some perturbation a NZ is initiated in the CS and it starts growing. The voltage that QD system is designed to detect contains both resistive and inductive signals and therefore the resistive signal can be masked by an inductive signal of the opposite sign. It means that at the time when the NZ voltage reaches the predefined threshold, it may not trigger a so-called hold. In order to trigger the hold, the total voltage needs to exceed the threshold. When the system registers a QD signal corresponding to the threshold (assume for example, 500-mV), the holding time starts, say 1.5 s. If during the following t_hold=1.5 s the signal doesn't drop below the threshold, a command for the CS current dump is issued by the QD analyzing circuit. It takes up to 0.5 s for the switchyard to open and commutate the current into the dump resistor. After that the current drops almost exponentially (slightly faster due to heating of the dump resistors that increases their resistance) and makes the energy extraction a little more efficient.

Otherwise, if the signal drops below the threshold, the system resets to the condition before the quench event.

II. Quench Detection with the Co-wound Voltage Sensors

The co-wound sensors are designed to provide a best possible coupling that would reduce the noise to a minimum. The theory of the QD co-wound sensors was developed in [8], and experimental demonstration and verification were reported in [9]. Basically, there are three sources of the noise: a) transverse field, b) longitudinal field and c) self-field noise [8].

The first source has to do with the fact that the magnetic field is not uniform in the radial direction and even not strictly linear. The loops that are exposed to the flux are different for the strands in the cable and the CVT that are outside of the jacket. As calculations show [10], the twist pitch of the co-wound wire is not important, but there is a net difference between the flux trapped by the CVT and the cable. Fortunately, for the CS scenario the difference is negligible.

The second source of inductive noise comes from the fact that the cable is formed by a multi twisting operation of the strand. Each cabling stage creates a little solenoid that traps the flux that generates an electromotive force [8]:

$$E = \sum_{1}^{N} \frac{\pi r_i^2}{l_p} \dot{B}_p \tag{1}$$

where N is number of the cabling stages, r_i is the effective radius of the subcable of "*i*" stage, measured by the centers of the previous stage subcables and $\dot{B}_p$ is the derivative of the longitudinal component of the magnetic field density.

For the CS modules, the longitudinal noise is negligible everywhere, except for the buses and termination extensions, which are sitting in the parallel field [10]. Therefore, the twist pitch of the CVT and RVT on the vertical runs of the conductor should be about 1.1 m for the baseline twist pitches established for the JACS PA in 2008. For the short twist pitches introduced by ITER IO in 2011, the recommended twist pitch of the QD tape sensor is 0.94 m. Relatively small difference in the twist pitch comes from the fact that the most dominant contribution comes from the last stage of cabling that did not change in both cabling patterns.

The third source of the inductive noise comes from the self-field. The CVT is outside of the jacket and therefore there is a significant flux between the cable and the coaxial voltage tap, explained in [8]. This source cannot be eliminated by smart twist pitch design; it is insensitive to it. The most efficient way to eliminate this signal is to subtract the signals from other DPs from the same module.

The CVT offers the best possible noise cancellation since the coupling between the CVT and the conductor is the possible best, inferior only to the sensor that is embedded inside the cable [9]. But even this method is not sensitive enough without reasonable management of the signals.

The electrical schematic of the QD based on CVT is shown in Fig. 2. In Fig. 2 we show the pairing of signals from the inlets of the CS module DPs. The voltage signals across the DPs are taken from the two wires: one is attached to the inlet of the previous (top to bottom) DP and another wire is attached to the inlet tube of the current DP. Note, for example the pair of voltage taps between the L2 inlet and the L3 inlet that after pairing go to cable 1 (main signal) and cable 2 (redundant signal). This works for the whole CS Module except the outmost pancakes, which have the voltage signal only from one pancake, including the bus and the coaxial joint.

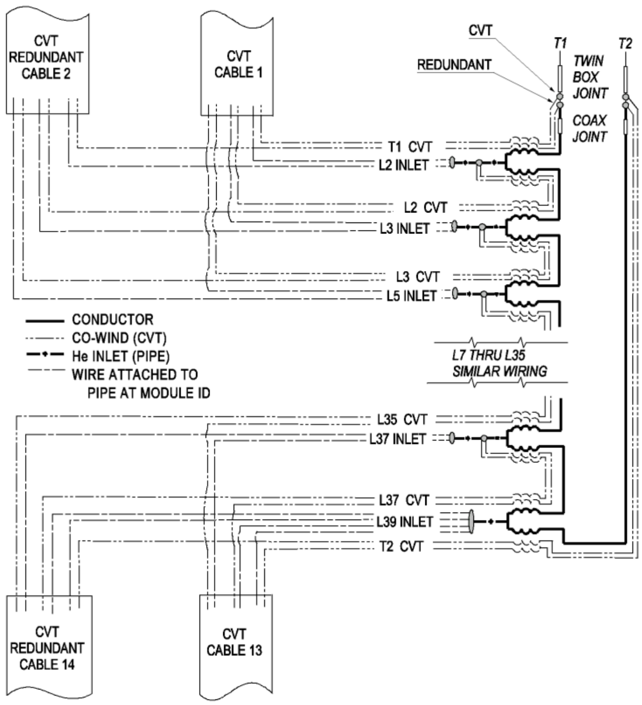

Fig. 2. Electrical schematic of the quench detection of the ITER CS module.

The guidelines for organizing the signals from the CVT are:

1) It is more convenient to extract the wires at the ID of the module than from the OD because signals at the OD need to be routed under the ground insulation of the plumbing. For the RVT we selected attachment points to be outlets, because signals from the ID would leave the outmost pancakes as single pancakes and make compensation for the RVT difficult or impossible. For the CVT it is possible to compensate the noise due to the self-field as explained below.

2) At the ID there is a certain probability that the normal zone may originate at one of the inlets and propagate symmetrically. In case of schematics where signals are subtracted one from the other, it may mask development of the NZ and leave the coil unprotected against such an event. That would lead to damage or destruction of the CS. In order to avoid that, the cancellation of the inductive noise will have to be done by subtracting signals from different parts of the CS. Evidently that would require elimination of the common mode high voltage that can be done by the electrical-optical converters; these converters would transmit the double or single pancake voltages to the control room, where they could be grouped in the configurations where the major noise source for CVT– self field – will be eliminated.

3) The number of the Quench Detection analyzing units can be reduced to reduce cost and increase reliability of the QD system. In order to meet all these requirements we proposed a scheme [11] with a minimum of two quench detection units (without redundancy). One unit will analyze the signal, which is the difference between the QD circuits cancelling voltage collected from pancakes (1,8,9,16,17,24,25,32,33,40) and (2,3,10,11,18,19,26,27) and another one - from pancakes (4,5,12,13,20,21,28,29) and (6,7,14,15,22,23,30,31). With this arrangement the three conditions discussed above are met.

III. Quench Detection with Regular Voltage Sensors

A. Central Difference Averaging

A relatively good first order cancellation of the inductive voltage noise can be achieved by so called central difference averaging, which can be done numerically or by an analog schematic as shown in Fig. 3.

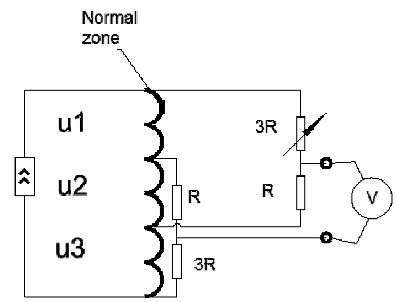

Fig. 3. Central Difference Average schematic for QD

In this case the voltage on the voltmeter is

$$V = 0.5u_2 - 0.25(u_1 + u_3) \qquad (2)$$

The compensation comes from the fact that the coil under QD watch is sandwiched between the adjacent coils, and the inductive noise cancellation will be to a higher order than just for two adjacent coils, say *u2* and *u1*.

However it was shown by MIT studies [2,12] and CEA studies [6,7] that only using CDA does not cancel the inductive noise to an acceptable level. An additional level of compensation is necessary.

A method, called Mutual negatives or MIK, was introduced in 2007 [4], where I and K stand for mutual coupling indexes of different circuits. The detail implementation of this method is described in [13]. The principle is that if one knows all the current derivatives of all sources of the inductive signals, the cancellation of the inductive noise can be done very efficiently. In other words, MIK cancellation means that the measured signal is modified in the postprocessor by subtracting expected inductive voltages from known sources. The attractiveness of this method is that the mutual inductance coefficients can be measured by exciting all the independent currents, one by one with the known dI/dt and measuring the inductive signals in all the QD circuits.

A similar idea was proposed and demonstrated on a simple multicoil system [14]. This schematic was never implemented in a real complex magnet system, but analysis shows [13] that this method is very promising and forgiving to the accuracy of the dI/dt knowledge or geometrical changes of the windings due to electromagnetic forces. Thus, RVT with MIK was selected to be developed and serve as a backup QD system to CVT method.

The RVT wiring schematic is shown in Fig. 3.

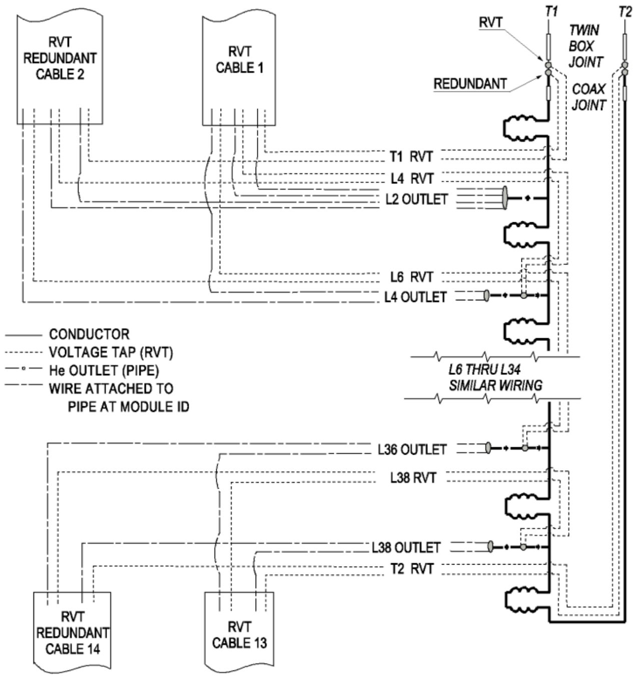

Fig. 4. QD with RVT

The signals from RVT for QD are taken from the OD. The voltage taps are paired: one is attached to the outlet of the next DP, say L4 outlet is paired with the voltage tap that is attached to the tube at the L2 outlet. Physically, the tube is attached to the outlet and routed to the ID of the CS and only there the voltage tap wire is attached, so the helium tube serves as a voltage tap conductor on this run from the OD to the ID of the CS.

Despite lower sensitivity than the CVT system, the RVT have some attractive features. In contrast to CVT, it is unlikely that the normal zone will ever originate at the OD, let alone propagate symmetrically due to vicinity of the joint near the outlet. Most important, the RVT taps are much better insulated from the conductor than the CVT and can be repaired.

IV. Numerical Modeling

Performance of both CVT- and RVT-based QD Systems was modeled numerically using Fortran computer programs simulating the sequence of events shown in Fig. 1. Two current scenarios were used for the analyses: 1) a 15-MA Normal Scenario, and 2) a Normal Scenario combined with a Vertical Displacement Event [15] during which plasma shrinks it's diameter and then drifts downwards gradually losing its current. Inductances were calculated [16] using stick models modeling CS conductor and cowound wire and also PF coils, the plasma and the passive structure.

The analyses showed that both QD systems are capable of suppressing inductive voltage to 25-50 mV with a holding time of less than 1.5-1.8 s, which with the account of the sensitivity (2) of CDA circuitry provides a signal to noise ratio of 10 for a 0.5 V Normal Zone resistance.

V. QD Summary

The design of the QD in the CS module contains two independent systems. One is based on the CVT. It has a high sensitivity and excellent cancellation of the inductive noise. The second QD system, which may be considered secondary, is based on RVT. It is not protected against inductive noise as well as the CVT system, but it is more robust, better insulated and it is reparable. Combination of these two systems gives us a high reliability QD system for the CS module.

Acknowledgment

We are thankful to Wayne Reiersen, Gary McGinnis, Robert Hussung, Phil Michael, Felix Rodrigues-Mateos, Marc Coatanea, Jean Luc Duchateau, Joel Schultz and Neil Mitchell for useful discussions and contributions to this project.

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